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Socio-ecological dynamics and inequality in Bogotá, Colombia’s public urban forests and their ecosystem services

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abstract Little is known about the distribution of urban forests of rapidly growing megacities in the developing world and what role they have on the well-being of citizens. Lack of information on their spatial distribution and ecosystem service (ESS) provision is especially pressing since megacities are often characterized by irregular land use patterns, social inequities, and socioeconomic instability.We explored spatial equity in key tree structural characteristics and ESS predictors from public urban forests in Bogotá, Colombia. We used one of the most comprehensive public urban tree inventories in Latin America, ESS indicators, and geospatial data to statistically and spatially analyze structural and diversity attributes and provision of ESS across Bogota’s land uses and socioeconomic strata. We found that the poorest socioeconomic stratum had the lowest tree size and crown attributes while the wealthiest stratum had the largest trees attributes. Tree diversity was greatest in northern, affluent areas and total C stocks were greatest in residential areas. Potential particulate matter removal was notably proportional to socioeconomic strata with the wealthiest having the greatest potential while the poorest stratum had the lowest. Residential land-use property value premiums were weakly related to tree diameter and height, and locality and socioeconomic strata were the most significant predictors of property value in residential land-uses. We identified marked inequalities in ESS provision by urban trees in Bogotá, Colombia highlighting a need for urban forest ESS to be taken into account in city planning efforts to address environmental justice issues and improve citizen welfare.

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1. Introduction

In many emerging countries, increased industrialization and civil unrest in rural areas have resulted in massive movements of people toward urban areas (De Geoffroy, 2009; Thibert and Osorio, 2013). In Latin America, the majority of the population lives in cities, making it one of the most urbanized regions in the planet. In Colombia,for example,more than75 percent ofthe populationlives in urban areas, and this trend is increasing over time (World Bank, 2013). The capital of Colombia, Bogotá, even before its founding in the mid-1500s, had a long history of urbanization and land use change (Andrade et al., 2013). As a result, Bogotá’s upper Andean ecosystems, which are some of the most diverse tropical mountain systems in the world (Myers et al., 2000), have been largely altered resulting in a rapid loss of environmental quality, biodiversity and ecosystem services (Alfonso Pina˜ and Pardo Martínez, 2014). However, despite the rate of urbanization in cities of the emerging world, such as Bogotá, relatively little is known about the distribution of urban and peri-urban forests

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and what their role is in improving the well-being of its citizens. Ecosystem services (ESS), the benefits that nature provides to humans, are often used to link urban vegetation structure to improved human well-being (Escobedo et al., 2011; Dobbs et al., 2011; Roy et al., 2012; Tzoulas et al., 2007). In Latin America, studies have linked the role of urban forests and their socio-ecological characteristics (Lima et al., 2013; Ordónez ˜ and Duinker, 2014), and revealed their capacity to provide ESS such as air pollution removal in Santiago, Chile and Mexico City (Escobedo and Chacalo, 2008; http://dx.doi.org/10.1016/j.ufug.2015.09.011 1618-8667/© 2015 Elsevier GmbH. All rights reserved. F.J. Escobedo et al. / Urban Forestry & Urban Greening 14 (2015) 1040–1053 1041 Fig. 1. Bogotá Colombia’s Capitol District (D.C.), study area. Dark green areas indicate major public urban forests. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.) Escobedo and Nowak, 2009), or energy use savings in San Juan, Puerto Rico (Brandeis et al., 2014; Santiago et al., 2014). Lack of information on the distribution of urban forest ecosystem service provision is especially pressing in the case of megacities in emerging countries, which are characterized by irregular and often unregulated land use patterns, social inequities, and socioeconomic instability (Dobbs et al., 2014a). Pedlowski et al. (2002) in Rio de Janeiro, Brazil, found that residents in high-income areas have better access to treed green spaces, and have a greater diversity of tree species. Similar findings have been reported in Santiago, Chile’s urban forests (De la Maza et al., 2002; Escobedo and Chacalo, 2008), while in Bogota, Colombia lower income neighborhoods had fewer street trees (Brown, 2012). In addition, people in lowerincome areas in San Juan, Puerto Rico, have reduced access to ESS and were excluded from green areas, thus explaining why survey respondents did not associate green areas with ecological benefits provided by urban neighborhood parks (Santiago et al., 2014). Equal access to, as well as amounts and distribution of, urban forests and ESS are often not guaranteed (Flock et al., 2011; Dobbs et al., 2014b) and effectively addressed in urban development planning policies (Heynen, 2003; Perkins et al., 2004; Santiago et al., 2014). Pedlowski et al. (2002) and Brown (2012) found disparities in public streets tree coverage among different neighborhoods in Brazil and Colombia, respectively. But, in cities in emerging countries – as opposed to those of North America and Europe – urban dynamics often follow unplanned development processes, due to deficiencies in land control, social inequities, and political instability (Aguilar et al., 2003; Kombe, 2005). Urban forest and environmental justice studies are abundant in industrialized countries and this is in large part due to the ease of research funding, easy and safe access, and available data and information (Heynen, 2003; Perkins et al., 2004; Flock et al., 2011). Nevertheless, public urban forests in emerging countries are commonly planted, conserved and maintained, and are considered of 1042 F.J. Escobedo et al. / Urban Forestry & Urban Greening 14 (2015) 1040–1053 Fig. 2. Bogotá D.C. Colombia’s localities (black lines) grouped into 5 major areas (in color). Note: Sumapaz locality (in the south Peripheral area) was not included in the study area due to lack of tree data. paramount importance in improving the social and environmental quality of life (Lima et al., 2013 Kendal et al., 2014; ; Dobbs et al., 2014a,b). However, to our knowledge, there is little information on the public urban forests of Latin American cities, their structural characteristics, and issues of equity in the provision of associated ESS. Therefore, the aim of this study is to explore the distribution of public urban forests in Bogotá, Colombia and their provision of key ESS, and analyze if indeed these are being provided equitably across space and the population. The use of field data, ecosystem service indicators, and available geospatial data can facilitate such statistical and spatial analyses across Bogotá’s land uses and socioeconomic strata. With the latter we mean an a priori administrative area defined by Bogotá’s regional government, which is based on household income, utility subsidies, and overall infrastructuredevelopmentinanarea (Thibert and Osorio, 2013).Hence, our specific research objectives are to:(1) analyze the dynamics and distribution in tree structure and diversity, and (2) estimate the role of public trees in influencing carbon stocks, particulate matter removal, and property price premiums across socioeconomic strata, neighborhoods and land uses. Such an approach will provide novel insights into the spatial and social dynamics of urban forests of megacities in the emerging world. 2. Materials and methods 2.1. Study area Bogotá, Capitol District (D.C.) Colombia’s administrative capital, has a population of approximately 7.5 million people and about 385 km2 of built urban area. The city is located at an elevation of 2600 m a.s.l., and has a subtropical highland climate according to the Köppen classification systems (Peel et al., 2007). Temperatures average 15 ?C, varying between 6 and 19 ?C, and total average F.J. Escobedo et al. / Urban Forestry & Urban Greening 14 (2015) 1040–1053 1043 Table 1 Ecosystem service, proxy indicators, and units of measurement. Ecosystem service (ESS) ESS proxy indicator Function Units of measurements Air quality improvement (Regulating) Tree crown removal of Particulate matter less than 10 microns (PM10) Air quality improvement by deposition of particulate matter Grams of potential PM10 flux per m2 tree cover Climate and micro-climate regulation (Regulating) Tree carbon (C) stocks Climate regulation via storage of CO2 and greenhouse gases Tree C kg per analysis unit Habitat and cultural Hulbert’s rarefaction index Biodiversity and sustainable provision of ecosystem services Tree species richness (S) Esthetics (cultural) Property price premium relationship Esthetic and amenity values Colombian pesos per m2 of property premium annual precipitation is approximately 824 mm (Andrade et al., 2013). The city is located within the tropical mountain vegetation type on a high altitude plateau of lacustrine and alluvial soils, bordered to the east by a mountain range and to the north and west by agricultural areas and wetlands (Alfonso Pina˜ and Pardo Martínez, 2014). The Andean montane forests host an exceptionally high biodiversity, varying significantly in composition according to altitudinal range, geomorphological conditions, micro-climate and soil types (Gentry, 1988). Public urban vegetation in the study area is managed and administered by the regional environmental district and municipal-level city government secretariats (Tovar Corzo, 2013). Major green spaces in the area of study are the 400 ha Parque Simon Bolivar and 20 ha Jardin Botánico;the 14,000 ha publically owned Cerros Orientales, or the eastern mountain range, that delineates the eastern boundary of the study area (Tovar Corzo, 2007; Andrade et al., 2013). The study area with all major public urban forests or green spaces is shown in Fig. 1. Since before Spanish colonization, the study area has experienced human settlements and continued land use changes. These legacy effects are expressed in its urban morphology and layout of its buildings, gray infrastructure (i.e. streets, drainage, utilities), peri-urban agricultural areas and wetlands dating back to the 1500s, as well as disturbed, cleared and reforested areas of adjacent secondary upper Andean forests. Rapid industrialization and past civil conflicts in rural Colombia have increased migration into the city, increasing its population from 5.5 million in 1995 to its current population and population density of 19,190 people/km2 (Andrade et al., 2013). The city has 20 localities, which we grouped into 5 major areas (Fig. 2);in general more affluent areas are located to the north and lower income areas to the south and west of the city (Thibert and Osorio, 2013). One locality was excluded from this study (Sumapaz), and since this was a semi-rural area, urban tree data was not collected. 2.2. Data collection and data preparation We used field data from Bogota’s extensive public urban tree inventory, which included taxonomy, structural and condition characteristics of each tree, as well as site attributes. During September 2005 to June 2006 forest engineers form Bogotá’s Distrital University and from Bogotá’s Botanical Garden measured all woody plants and palms greater than 30 cm in height located on all public, urban, land uses in Bogota (Manual del Cencista, 2006). Specific biometric data used in our structural analysis included tree genus and species, diameter at breast height (DBH; diameter at 1.3 mabove the surface),total height, crown width and spatial coordinates. Specific details and measurement methods can be found in Manual del Cencista (2006). Overall, more than 1 million individual trees were measured in this inventory, making this to our knowledge, the most comprehensive public urban tree inventory in Latin America. To differentiate tree and palm growth forms from shrubs in subsequent analyses, we only included individuals that were:(1) greater than 2.0 m in height, (2) greater than 2.5 cm in DBH, and (3) identified to the species level. The final number of trees analyzed (n = 445,123) presents a unique, statistically robust, and spatially representative sample. We used the tree inventory and the literature to estimate a series of proxy indicators representing relevant ESS provision in the urban environment. We then used publically available geospatial data sets, as well as statistical and geospatial analyses to spatially characterize the tree attributes and indicators across space. Specifically, based on Dobbs et al. (2011), Escobedo and Chacalo (2008), Donovan and Butry (2010) and Pandit et al. (2013), we estimated potential air pollution removal by tree crowns as a proxy for air quality improvement and aboveground carbon storage (Escobedo et al., 2010) as a proxy for climate regulation. We also calculated tree diversity as a proxy for habitat and cultural ESS, and we used the relationship between tree size and property price premiums as a proxy for cultural ESS (Table 1). 2.2.1. Tree carbon stocks Estimates of urban forest carbon stocks are important for locallevel climate change mitigation plans and for participation in carbon offset markets (Denman et al., 2007; Horn et al., 2015; IPCC, 2007). Accordingly, allometric and volumetric biomass equations were used to determine individual total tree carbon stocks based on species, DBH, height and published wood densities (Henry et al., 2013; see Appendix A for details and additional references). Available above-ground biomass equations were assigned to individuals at the species level where possible. If species-specific equations were not available, genus, family or growth from-specific equations were assigned (Appendix A). Following a commonly used assumption, dry weight tree biomass was then converted to carbon stocks by multiplying dry weight biomass by 0.5 (Escobedo et al., 2010). 2.2.2. Tree diversity Species diversity is closely related to ecosystem function and subsequent services. Indeed, two main ecological system properties related to species richness are resilience and resistance (Chapin et al., 2000). The presence of functional redundancy in species composition provides a form of ‘probabilistic insurance’ that some species can survive a particular environmental or human-induced stressor, thus making more difficult a change in ecosystem properties (Chapin and Shaver, 1985; Nagendra and Gopal, 2010). In the urbancontexttreehealthand pest problems are particularly important, and species richness has a crucial role in increasing an urban forest’s resilience to pests and diseases (Burdon, 1993; Kendal et al., 2014). Tree species composition is commonly measured using species richness and various diversity indices. Many diversity indices, however, have the drawback of being sample size-dependent. In our study the number of trees differed substantially among the

Table 2 Geospatial and socioeconomic data sources used in analyzing Bogota Colombia’s public urban trees. Data Description Source Tree

attributes Tree coordinates, species, diameter at breast height (cm), height (m), crown area (m2) Manual del Cencista (2006) Property value premium per square meter Property value per m2 in Colombian Pesos. Departamento Administrativo Nacional de Estadística (DANE) Socioeconomic strata Estrato or socioeconomic classes in Bogotá on a scale from 1 to 6. Infraestructura de Datos Espaciales para el Distrito Capital (IDECA)a Land use type Parcel-level land use classes IDECAa Locality Localidad or neighborhood level localities IDECAa a http://www.ideca.gov.co/index.php?q=es/content/cat%C3%A1logo-de-datos-geogr%C3%A1ficos. different stratificationunits;thus, evaluating species richness using standard diversity indices could lead to biased conclusions due to different sample sizes. To overcome the issue of unequal sample size, we used Hurlbert’s rarefaction measure (1971), as modified from Sanders (1968), to better describe the expected number of species in sample size n, drawn from a population of size N with S species: ES(n) = S i=1 1 - N - Ni n / N n (1) where N is the total number of individuals in the population, Ni is the number of individuals ofthe ith species in the population, and n is the number of individuals in the subsample. Hurlbert’s expected number of species was calculated by socio-economic strata with n equal to the smallest sample among strata, and by Bogota’s localities with n equal to the smallest sample among the localities, to investigate access of habitat and cultural ESS at the social and spatial level, respectively. 2.2.3. Tree potential pollution removal The air pollution deposition function of urban trees and their effect on air quality has also been well documented as a key ESS in many cities including those of LatinAmerica (Escobedo and Chacalo 2008; Roy et al., 2012). Urban tree biometrics along with weather and pollution concentration data have been regularly used along with simulation models to estimate the dry deposition flux (F; g) of air pollutants to tree crowns given specific leaf area and pollutionweather characteristics (Escobedo and Nowak, 2009). Given the lack of availability ofthe requiredurbanforest structureparameters (e.g. leaf area, leaf biomass and leaf area index) and appropriately formatted hourly weather and pollution data for Bogotá necessary for these models, we used a simplified potential pollution flux model: F = vd * C. In this model, deposition velocity (vd; g cm-1) and Particulate Matter less than 10 microns in diameter (PM10) concentrations (C; g m-3) were used to estimate the effect of individual tree crown cover on potential ambient pollution concentrations removal (g m-2 of tree cover; see Escobedo and Nowak, 2009). To apply the simple potential pollution flux model, a measured individual tree’s crown diameter (m) was converted to crown area (m2) and multiplied by average annual PM10 pollution concentration (g m-3) and tree crown deposition velocities (vd; g cm-1) from another South American city, Santiago, Chile using an approach similar to Escobedo and Nowak, (2009) and Escobedo and Chacalo (2008). Mean annual PM10 concentration for 2006 (68 g m-3) was obtained from RMCAB (2006). We note that this potential pollution removal approach does not account for individual tree leaf area indices, evergreen composition and periods of wet deposition. As such, it is not comparable to other more quantitative modeling studies (Escobedo and Nowak, 2009). But, given the lack of necessary parameters and data, it does provide an approximate potential pollution removal indicator that can be used to compare the relative potential role of tree cover in particulate matter removal across the study area. 2.2.4. Tree-related property price premiums Several studies have analyzed the role of street trees and tree cover on real estate prices (Donovan and Butry, 2010; Pandit et al., 2013). Using hedonic econometric analyses of urban tree attributes (e.g. tree cover and numbers) along with home attributes (e.g. area, number of bedrooms, and bathrooms) and real estate premiums, these studies have modeled the influence of specific tree and home attributes on property values.

Increased tree cover and numbers have generally been found to be positively related to real estate premiums (Donovan and Butry, 2010; Pandit et al., 2013). Hence, we used this well documented econometric relationship between measured tree DBH and property values from available geospatial data as a statistical predictor for the effect of tree size on property values. 2.2.5. Socioeconomic and spatial data We analyzed our four ESS indicators by stratifying our sample according to three major socioeconomic categories or stratification units to better characterize the socioeconomic, geographic, and land use conditions of the tree population and its ESS (Table 2). Our first division was Socioeconomic strata (Escobedo et al., 2006; Thibert and Osorio, 2013). It is defined by Bogota's regional government on a scale from 1 to 6, where 1 denotes urban areas represented by very low income housing, frequent unpaved roads and low access to urban infrastructure (e.g. water and electricity access, sewage, etc.), while 6 represents high-income housing access to very well-developed infrastructure and utilities. We do note that 171,237 trees in our dataset were located in areas without a designated socioeconomic strata or outside municipal boundaries; accordingly, these tree were not included in descriptive statistics or subsequent analyses. Asecond stratification was land use type, defined by the regional planning authority zoned land uses, including residential, institutional, commercial, and industrial/commercial (Table 2). Land-use is known to be a significant factor in driving ESS in urban ecosystems (Davies et al., 2013; Dobbs et al., 2011). Trees located in areas without a designated land use were notincluded in statistical models (n = 31,899). Finally, our third division was Localidad, or locality, referring to the 19 unique areas intermediate to municipalities and neighborhoods in scale. These localities have grown in number and characteristics following city expansion over time. For subsequent analyses we collapsed the 19 units into five major urban areas (Fig. 2) to facilitate geographic characterization and data interpretation. 2.3. Statistical analyses Models were estimated for individual tree structure and ESS indicators. A mixed model framework was investigated to assure F.J. Escobedo et al. / Urban Forestry & Urban Greening 14 (2015) 1040–1053 1045 Table 3 Bogotá Colombia's public urban tree structure according to average tree diameter at breast height (DBH), height, crown area, and estimated per tree carbon stocks. # Trees DBH (cm) Height (m) Crown area (m2) Per tree carbon stocks (kg) Total carbon stocks (tons) Avg. SE Avg. SE Avg. SE Avg. SE Land-use class Commercial 10,844 27.0 0.22 8.25 0.06 44.1 0.60 290.5 7.4 3150 Industrial/commercial 6994 19.2 0.20 8.45 0.07 24.9 0.38 179.8 8.7 1257 Institutional 12,666 20.2 0.14 8.26 0.04 30.7 0.34 180.2 7.8 2282 Residential 382,718 18.7 0.03 7.06 0.01 24.8 0.06 172.0 1.3 65,808 Not classified 31,899 16.9 0.08 10.34 0.04 21.2 0.15 124.8 2.7 3982 Socioeconomic strataa 1 10,421 12.7 0.13 6.33 0.06 15.6 0.27 111.1 6.9 1158 2 70,874 15.7 0.06 6.75 0.02 19.7 0.12 141.8 3.0 10,050 3 99,501 19.6 0.05 6.81 0.01 24.7 0.11 151.8 1.8 15,104 4 37,974 22.9 0.10 7.39 0.03 31.3 0.23 227.1 3.6 8624 5 29,948 20.8 0.12 7.69 0.03 30.3 0.24 214.2 5.2 6415 6 25,166 23.6 0.15 8.09 0.04 34.4 0.31 303.0 8.0 7625 Avg., average; SE, standard error. a Does not consider 171,237 trees located in areas without a designated socioeconomic strata. correct accounting for sampling dependencies due to spatial autocorrelation in Bogotá's public urban forest structure and ESS provision. Due to the size ofthe dataset,the models were developed in two steps. First,the SAS procedure PROC MIXED (SAS version 9.4; SAS Institute Inc., 2011) was used to estimate fixed-effects general linear models for each tree structure and ESS variable by land use class, withallpossible covariates andinteractions, andproduce spatially explicit residuals. Empirical variograms ofthemodel residuals were then estimated via the SAS procedure PROC VARIOGRAM and eight possible spatial autocorrelation structures were investigated from the Gaussian–Matern class of models (Goovaerts, 1997;

Section 4.2.4). In each of the data subsets for each variable of interest, there were no significant spatial autocorrelation patterns found, and thus no spatial auto-correlative structures were included in subsequent analyses. First, simple models were estimated for tree structural attributes (DBH, height, crown area), as well as tree C stocks, pollution removal, and property values, to test for differences among land use classes and socioeconomic strata via the SAS procedure PROC GLM. Where significant differences were found, pairwise comparisons were made via the Bonferroni procedure. More complex models were then formulated for tree C stocks and property values for each ofthe five land use types. Tree C stocks were modeled and tested using tree DBH and DBH2 (as a proxy for cross-sectional area of the tree), tree height, and price premium of the nearest property to the tree as predictor variables. In addition, we included all two-way interactions with localities and socioeconomic strata. Similarly, property premiums were modeled with tree DBH and DBH2, tree height, and tree C stocks, as well as all two-way interactions with localities and socioeconomic strata as predictor variables. In the non-residential class, 31,380 trees were missing property values; subsequently these were excluded from further analyses. Both tree C stocks and property values were logtransformed to meet normality and homoscedasticity assumptions. Non-significant ($P < 0.05$) predictors were dropped from analyses as long as it resulted in a better (lower) value of the Akaike Information Criteria (AIC). Where significant effects were found, marginal (least-square) means were generated to facilitate comparisons between effect levels. Hurlbert’s expected species richness (or ‘rarefied species richness’) was calculated using an ad-hoc routine from the Vegan Community Ecology Package in the R statistical computing software (Oksanen, 2013). We obtained comparable expected species richness in random subsamples using 1000 iterations of the minimum sample size (i.e. individual trees) among the statistical units of the two stratifications used (i.e. socioeconomic strata and 0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100% Strata 1 Strata 2 Strata 3 Strata 4 Strata 5 Strata 6 Percent of Maximum Average Value DBH (cm) Ht (m) Crown Area (m2) Fig. 3. Percent of maximum average value of urban tree structure attributes for Bogota, Colombia versus socioeconomic strata: height (Ht), diameter breast height (DBH), and crown area. locality). Standard errors (se) associated with each E(S) estimate were calculated following Heck et al. (1975). 3. Results 3.1. Urban tree structure Because of the large number of observations, statistical tests of tree structure variables were very sensitive to small differences in effect sizes, i.e. small differences in the value of structural variables due to changes in the explanatory variable were statistically significant in the models (Table 3). Average tree DBH and crown area in all land use and socioeconomic strata were significantly different ($P < 0.001$), with the exception of residential areas which were not significantly different ($P > 0.05$) from industrial/commercial. Tree height was significantly different ($P < 0.001$) in all land use types except for among commercial, industrial/commercial and institutional, and in all socioeconomic strata, except for 2 versus 3. Total C stored in Bogota’s public trees was 76,500 tons and approximately 85% of stocks were in residential areas (Table 3). Overall, commercial land uses had the trees with the largest diameter and crown area, while residential land uses had trees with smallest diameter and crowns. Overall, the average tree structural attributes (DBH, height, crown area) show distinct and proportional linear trends according to socioeconomic strata (Fig. 3). Strata with 1046 F.J. Escobedo et al. / Urban Forestry & Urban Greening 14 (2015) 1040–1053 Fig. 4. Tree diversity index distribution (Hurlbert’s index). Black lines delineate the five major areas in the city. Numbers identify the locality name in Table 5b. better socioeconomic conditions were characterized by taller and larger trees (DBH, height, crown area), while tree in poorer socioeconomic strata were smaller in terms of size (e.g. strata 1 and 2). 3.1.1. Tree carbon stocks Results from our simple model indicate that tree C stocks in commercial land uses were significantly different from all other land use classes (P < 0.001), whereas residential, institutional, and industrial/commercial land uses were not significantly different from each other (P > 0.05). Tree C stocks in socioeconomic stratum 2 were not significantly different from 3, and stratum 4 was not different from 5 (P > 0.05). Otherwise, C stocks in all localities and socioeconomic strata were significantly different. The more complex tree C stock model included additional predictors. We found that in all land-use types, except for that of residential, property value was not a significant predictor of carbon and thus was dropped from the model. In residential land uses, we found that the effect of property value was significant, but its inclusion led to unstable model parameter estimates; therefore it was dropped and resulted in a very minor change in AIC. As in the simple model estimated for C stock, the complex models were very sensitive to small differences in predictor effect sizes due to the very large dataset. For all land uses except institutional, all two-way interactions of with socioeconomic strata and locality were found to be significant predictors of tree C stocks (Table 4). For institutional land uses, the effect of locality could not be estimated due to limited numbers of observations across the sampling area. We observed a positive trend in C stocks according to socioeconomic stratum, but the trend depended on DBH and height, and varied among land uses. Marginal means, which isolate the effect of the variable of interest while holding all other variables at their average values, were estimated to identify trends in tree C stock over tree DBH and height according to localities and socioeconomic strata, as well as locality and socioeconomic stratum combinations. We found that DBH was the strongest predictor of F.J. Escobedo et al. / Urban Forestry & Urban Greening 14 (2015) 1040–1053 1047 Table 4 Type III tests of fixed effects for predictor models of log of carbon (C) by land use class in Bogotá D.C. Colombia’s public urban forest. Boldface type denotes most important predictors in each land use. Effect Comm. (n = 7935) Inst. (n = 2153) Ind./Comm (n = 4011) Res. (n = 253,240) F Value Pr > F F Value Pr > F F Value Pr > F F Value Pr > F Strata 30.83 <.0001 16.14 <.0001 6.68 <.0001 117.63 <.0001 Locality 9.14 <.0001 8.13 <.0001 50.6 <.0001 Strata × Locality 16.23 <.0001 2.34 0.0967 18.61 <.0001 DBH 50.57 <.0001 293.67 <.0001 11.55 0.0007 81216.7 <.0001 DBH × Strata 18.66 <.0001 2.85 0.0227 35.31 <.0001 231.04 <.0001 DBH × Locality 13.45 <.0001 34.34 <.0001 142.94 <.0001 DBH2 6.22 0.0127 96.71 <.0001 4.09 0.0432 20652.1 <.0001 DBH2 × Strata 36.13 <.0001 1.94 0.1006 43.74 <.0001 288.77 <.0001 DBH2 × Locality 9.56 <.0001 23.92 <.0001 274.04 <.0001 Height 2.85 0.0917 9.48 0.0021 0.1 0.7563 1578.38 <.0001 Height × Strata 38.01 <.0001 34.94 <.0001 12.43 <.0001 15.56 <.0001 Height × Locality 6.43 <.0001 14.32 <.0001 39.39 <.0001 Comm., commercial; Inst., institutional; Ind., industrial; Res., residential. Table 5a Bogota, Colombia’s public tree diversity as estimated using the Hurlbert’s rarefaction E(S) according to socioeconomic strata (n = 10,421 trees). Socioeconomic strata (n = 10,421) 1 2 3 4 5 6 E(S) 136 154.37 156.77 170.07 154.75 158.23 Standard error 0 3.93 4.04 3.68 3.47 3.47 Table 5b Bogota Colombia’s public tree diversity as estimated using Hurlbert’s rarefaction E(S) according to locality and area (n = 2504 trees). Bold indicates high diversity values. Locality ID Locality name Area E(S) Standard error 1 Usaquen Northern Foothills 120.62 4.47 2 Chapinero Northern Foothills 114.75 4.39 3 Santa Fe Center 110.66 3.98 4 San Cristobal Southern Periphery 100.69 3.64 5 Usme Southern Periphery 84.2 3.77 6 Tunjuelito Southern Periphery 83.61 3.16 7 Bosa West 93.7 3.05 8 Kennedy West 98.58 3.89 9 Fontibon West 100.61 3.85 10 Engativa Northern Periphery 102.61 3.65 11 Suba Northern Periphery 117.53 4.17 12 Barrios Unidos Northern Periphery 93.75 3.77 13 Teusaquillo Center 113.07

4.00 14 Los Martires Center 86.0 0 15 Antonio Nari˜no Center 91.63 2.25 16 Puente Aranda Center 102.62 4.10 17 Candelaria Center 96.78 1.68 18 Rafael Uribe Southern Periphery 97.11 3.36 19 Ciudad Bolivar Southern Periphery 86.25 3.46 Table 6 Average (Avg.) pollution removal capacity and property premiums for Bogotá D.C. land-use classes and socio-economic strata. SE = standard error. Pollution removal (g m-2 crown area) Property value premium (Colombian pesos) Avg. SE Median SE Land-use class Commercial 291.1 3.93 $389,675 $2061 Industrial/commercial 164.5 2.53 $359,008 $995 Institutional 202.9 2.22 $84,000 $251 Residential 163.4 0.40 $203,476 $217 Not classified 140.0 0.99 n/a n/a Socioeconomic strata 1 103.0 1.77 $59,065 $1075 2 129.8 0.82 $126,699 $247 3 163.2 0.72 $201,613 $246 4 206.3 1.49 $292,753 $563 5 199.7 1.61 $369,762 $712 6 227.2 2.04 $439,654 $1286 C stock (Table 4), which was not unexpected, given the allometric equations used in its estimation (Appendix A). In general, C stocks increased with DBH and height in all land uses. In commercial and industrial/commercial land uses,the increase in C with DBH tended to be stronger as socioeconomic strata increased (i.e. became more affluent), whereas in institutional and residential land uses, the trend tended to be opposite. Conversely, in all land uses except institutional, the increase in C stock according to increased tree 1048 F.J. Escobedo et al. / Urban Forestry & Urban Greening 14 (2015) 1040–1053 100 120 140 160 180 200 220 240 1 2 3 4 5 6 F (g yr-1 m-2) Socioeconomic Strata Fig. 5. Estimated potential air pollution removal (F; grams particulate matter less than 10 microns per square meter tree cover) by Bogota Colombia’s public urban trees versus socioeconomic strata. Note: Strata 1 is the poorest and strata 6 the most affluent. heights tended to be weaker as socioeconomic strata increased. In particular increased C stocks in residential land uses increased as the socioeconomic strata became more affluent. But, we observed no patterns or trends according to locality. 3.1.2. Tree diversity Tables 5a and 5b show the values of Hurlbert’s rarefaction measure (E(S)) and standard errors for each socioeconomic strata and localities. The poorest socioeconomic strata (1)indeed had the lowesttree diversity as estimated using Hurlbert’s rarefaction measure (136; Table 5a) and the Los Martires locality – in socioeconomic strata 1 and in the urban central core of Bogotá – had the lowest tree diversity (86; Table 5b). Otherwise, we could not discern a clear global relationship relating tree diversity with socioeconomic strata (Table 5a).Higher treediversity values were,however, clearly observed in localities 1 (Usaquén), 2 (Chapinero) and 11 (Suba), all belonging to the northern urban-peri urban areas, that include the richest socioeconomic strata as well as prime agricultural areas in what is known as “Bogotá’s savannah” (Fig. 4). 3.1.3. Potential air pollution removal The simple models identified significant differences in potential air pollution removal by public urban trees across all pairwise comparisons of land use class, with the exception of industrial/commercial which was not significantly different from residential (P < 0.01; Table 6). All socioeconomic strata were also significantly different from each other in terms of potential air pollution removal. Commercial areas had the highest potential air pollution removal potential, while industrial areas had the lowest. Localities in the northern foothills (e.g. Chapinero) had the greatest potential air pollution removal, while Southern peripheral areas (e.g. Usme) had the lowest. Overall, potential air pollution removal tracked exactly the same as crown area because of its linear estimation function; it was notably correlated to socioeconomic strata, with 6 having the greatest and 1 the lowest potential (Fig. 5). 3.1.4. Tree-property value premium relationships Results from our simple model show that tree property value premium relationships were significantly different across all land use and socioeconomic classes (P < 0.0001; Table 6). Additionally, the complex models thatincluded as predictors tree DBH and DBH2, and height, and their interactions with land use and socioeconomic class, indicated significant differences (P < 0.001) across all localities and socioeconomic strata (Table 7). In residential land uses, tree C stocks and their interactions with locality and socioeconomic strata were also significant predictors. Overall, in residential land-uses, property value premiums increased as tree DBH, height and C increased, as well as in socioeconomic strata when all other variables in the model were held at their average values. In particular locality and socioeconomic strata were the most significant predictors of property value premium in residential land-uses with localities the Northern Foothills exhibiting the largest influence of tree height on property value premium relationships (e.g. Usaquen, Chapinero). Although DBH and C were statistically significant in the model, we observed only a slight increasing trend in their relationship to property value premium in each locality and socioeconomic strata.

4. Discussion

Our findings indicate statistically and spatially different urban forest structural attributes and ESS indicators with respect to socioeconomic strata, land use, and localities in Bogotá, Colombia. Analyses were also extremely sensitive to even small effect sizes, due to the large sample size. Nevertheless, this evident unequal provision in public urban forests and their ESS across Bogotá’s socioeconomic strata, land use types and localities will subsequently affect the quality of life of its citizens. These marked differences (Tables 2–7; Figs. 3–5) have been documented elsewhere, as discussed in our literature review. However, this study is one of the first in the international literature discussing these city wide trends using tree inventory data from over half a million trees and available geospatial data from a megacity in an emerging country in Latin America. These findings are likely a result of complex socioeconomic and biophysical interactions among multiple drivers such as legacy effects of the historical expansion of the city, past and ongoing civil unrest in the country, emigration trends, resource availability and irregular land use and urban development patterns (De Geoffroy, 2009; Kowarik, 2011; Andrade et al., 2013; Lima et al., 2013; Tovar Corzo, 2013). In particular, immigration fluxes from the rest of the country to the capital have driven recent land use and urban planning priorities. This immigration often occurs in peri-urban areas, which correspond to the poorest socioeconomic strata (1 and 2) in our study area and in particular the Southern Peripheral localities in Bogotá (Fig. 2). De Geoffroy (2009), for example, documented how people displaced from armed internal conflicts in Colombia’s rural areas settled in Bogota’s peri-urban fringe, placing massive pressure on existing remnant and urban forests. The same author reports an estimated 625,000 persons settling in the outskirts of the city between 1985 and 2006, leading to uncontrolled and illicit urbanizations (‘barrios piratas’). As a consequence, Bogota’s periurban fringe is often characterized by a lack of organized urban developments, zoning enforcement, lack of public security and thus proper urban forest management (Thibert and Osorio, 2013).

4.1. Structure

Tree DBH, height, and crown area in this study were correlated with increasing socioeconomic strata (Fig. 3). Similarly, older and more affluent areas in the Eastern Foothills and Northern Foothills and Periphery had larger, taller tree with larger crowns (Table 3). Building densities in Bogotá’s lower socio-economic strata are higher than in more affluent strata (i.e. strata 5 and 6; Thibert and Osorio, 2014); as such increased impervious areas will limit available tree growing and planting spaces. Analysis of street tree numbers in lower and higher income neighborhoods in Bogotá have indicated that poorer areas experienced a noticeable lack of street trees (Brown, 2012). Management practices and social dynamics have also been documented as affecting tree numbers and attributes in Colombian cities (Tovar Corzo, 2007).

Table 7 Type III tests of fixed effects from mixed model analysis of log of property value premium relationships

according to two broad land use class, residential and non-residential. Note bold indicates most statistically important predictors. Effect Non residential (n = 14,099) Residential (n = 253,240) Num DF F Value Pr > F Num DF F Value Pr > F Strata 4 64.09 <.0001 5 4250.00 <.0001 Locality 13 1311.04 <.0001 18 2052.11 <.0001 Strata × Locality 13 280.43 <.0001 43 2221.58 <.0001 DBH 1 1.76 0.1848 1 217.84 <.0001 DBH × Strata 4 43.11 <.0001 5 118.69 <.0001 DBH × Locality 13 25.88 <.0001 18 100.75 <.0001 DBH2 1 0.17 0.6823 1 118.66 <.0001 DBH2 × Strata 4 13.38 <.0001 5 45.67 <.0001 DBH2 × Locality 13 7.17 <.0001 18 26.30 <.0001 Height 1 0.16 0.6895 1 385.47 <.0001 Height × Strata 4 29.62 <.0001 5 121.79 <.0001 Height × Locality 13 39.05 <.0001 18 256.70 <.0001 Carbon 1 0.04 0.8332 1 17.93 <.0001 Carbon × Strata 4 2.61 0.0335 5 6.19 <.0001 Carbon × Locality 13 1.43 0.1375 18 11.93 <.0001 4.2. Tree carbon stocks We found significant differences in tree C stocks among localities and socioeconomic strata, in particular in commercial areas and high income strata (Tables 3 and 4). Although, tree C stocks are an ESS relevant at a global scale, its unequal spatial distribution has local-scale implications for spatial variability of this indicator and represents a measure of inequality in tree biomass and overall microclimate regulation. Climate regulation via C sequestration is considered a major ecosystem service because of its role in mitigating atmospheric CO2 (Farquhar, 1997; Escobedo et al., 2010; Roy et al., 2012; Ordónez ˜ and Duinker, 2014). Therefore, this ESS could contribute to Bogotá’s ability to mitigate predicted adverse effects of climate change in the Northern Andes (Poveda et al., 2010). However, overall net C stocks will change over time and will depend not only on biomass but also on condition, composition, and maintenance emissions as well as on methodology (e.g. allometric equation, crown-to-shoot-ratio; Horn et al., 2015). Also, although not directly analyzed, buildings with more tree shade will also influence energy consumption and related greenhouse gases emissions from buildings cooling (Flock et al., 2011). 4.3. Tree diversity Our tree diversity results also show marked differences among land-use classes and localities in Bogotá (Tables 5a and 5b, Fig. 4). Higher species richness was found in the Northern locality area, which contain large areas of high income socioeconomic strata; thus demonstrating an unequal distribution of this service. Although, we observed no significant differences among socioeconomic strata, socioeconomic strata 1 had much lower species diversity. Such differences in species richness among localities and other strata are well documented in the literature (e.g. De la Maza et al., 2002; Nagendra and Gopal, 2010; Conway and Bourne, 2013). Also, differences in tree diversity in Bogotá might be due to changing tree planting preferences and legacy effects from past demographic changes. For example, tree planting strategies in Bogota’s differentlocalities from 1998 to 2004 indicated changes in planting preferences for specific tree species (Tovar Corzo, 2007). In North America Boone et al. (2010) also demonstrated that demographics and neighborhood lifestyle characteristics in the 1960s – and associated tree planting preferences – are correlated to current urban forest characteristics. 4.4. Tree pollution removal potential Our findings indicated notable differences in air pollution removal potential by Bogotá’s trees according to land use and socioeconomic strata (Table 6). Overall, we found a significant relationship between PM10 pollution removal and increasing socioeconomic strata (Fig. 5). In particular,the wealthiest socioeconomic stratum (6) pollution removal potential was almost twice that of the poorest strata (1 and 2), and as a result, shows a spatially heterogeneous, and unequal provision of this ESS across Bogotá. Although PM10 concentrations in this study were assumed to be constant across the city, in reality pollutant concentration will vary across space (Escobedo and Nowak, 2009); but this was not accounted for due to lack of data. Since concentrations were kept constant across the study area, tree crown area drove this trend. 4.5. Property values Tree-property value premium relationship averages were significantly different across all land use and socioeconomic strata (Table 7). Trees in localities in the Northern Foothills (e.g. Usaquen, Chapinero) had noticeably higher property value premiums. We observed that locality and socioeconomic strata were indeed the most significant predictors of tree-property value premium relationships in residential land-uses. Overall we observed only a slight increasing trend in property value premiums as tree height, DBH, or C stocks increased in each locality and socioeconomic strata, with height being the most important predictor. Hedonic valuation method studies from industrialized countries (e.g. Unites States, Australia) frequently use the econometric relationship between tree-house attributes and the real estate value of a property (Donovan and Butry, 2010; Pandit et al., 2013). However, we note that we are only reporting the statistical relationship between structural predictors and property value premiums and are not implying a direct, causal relationship between tree size and real estate clearing prices. Furthermore, Ordónez ˜ and Duinker (2014) discuss the perception of Colombian urbanites on the cultural ESS and values provided by the urban forests of Bogota, Pereira and Cali. Interestingly, they found that increased property values from urban forests were not a top concern for study participants. This might be a result of the frequent occurrence of informal economic activities (e.g. street vendors, intermixed commercial/residential/recreation activities near treed spaces) that are very common to the Latin American context. Although these types of studies differ in the method and the type of valuation (held versus assigned values), care is needed when assuming that ESS of interestto industrialized countries are the same as those prioritized by beneficiaries from emerging countries with very different contexts (Escobedo et al., 2011; Roy et al., 2012; Ordónez ˜ and Duinker, 2014). 5. Conclusion Findings from this study are based on an approach that used available geospatial data and one of the most comprehensive and extensive public urban tree inventories in Latin America. However, we do note our lack of available data such as ambient pollution concentrations across the study area, detailed tree crown characteristics, some species specific allometric equations and other geospatial demographic data thatis commonlyused insimilar studies from North America, Europe and Australia. Similarly, we do not account for the ecosystem disservices (allergies, tree damage to infrastructure, litter) and management costs (labor, maintenance, administration) that are required to better understand the overall net benefits – and costs – of an urban forest. An additional relationship that is not well understood is the role of diversity on ESS, and the spatial heterogeneity in the public’s demand for specific ESS or disservices such as the perception that increased tree density and cover is related to increased crime. These limitations do, however, provide opportunities for future research. Despite these limitations, our findings contribute toward a better understanding of the patterns of ESS across Bogota’s public urban forests. Information from this study could also be used along with other available literature to better address urban environmental justice issues in other cities in emerging countries. As such, this and our study could be used along with recommendations from Bogotá-relevant publications in our introduction to develop guidelines to better plan, manage, design and equitably distribute pubic urban forests in Bogotá. Principles of environmental justice aim for an equal access and provision of ecosystem services throughout a city and to all groups of beneficiaries. We demonstrated a marked unequal distribution of four different ESS in the city of Bogotá. This supply and demand for ESS should be participatory and inclusive of all income groups and citizenry. But, our findings and other literature indicate that upper income strata have a substantially better access to the services provided by the city’s urban forest, while lower income strata receive fewer benefits due to a smaller-sized and less dense urban trees community. Furthermore, we surmise that this can also be a result of available growing space as well as weak governance and/or lack of willingness of the local government to counteract uncontrolled and unplanned urban developments. This study highlights the importance of accounting for urban forests and ESS in city planning efforts in emerging countries, in order to better provide equal access to the panoply of benefits that contribute to better quality of life for all citizens. Acknowledgements We acknowledge the Jardín Botánico José Celestino Mutis, Subdirección de Silvicultura, Flora y Fauna Silvestre, Secretaría Distrital de Ambiente, Alcaldia Mayor de Bogotá, Colombia, Sector Ambiente for providing the urban tree inventory data. We thank Benjamin Himschoot for acquiring key geospatial data. Andrea Acuna˜ and Luciano Hildenbrand Penuela ˜ are also acknowledged for compiling tree species allometric information. Appendix A. Bogotá’s, Colombia, public tree species list and source of allometric biomass equations used for carbon stock estimates. Tree genus-species Biomass (B) or volume (V; units) Sourcea Casuarina equisetifolia B (cm, m, kg) http://www.globallometree. org/data/equation/28128/ Chionanthus pubescens B (cm, kg) http://www.globallometree. org/data/equation/30893/ Fraxinus chinensis Jasminum humile Ligustrum japonica Ligustrum lucidum Olea europaea Populus nigra italica B (cm, m, kg) L.M. Zabek, C.E. Prescott. 2006. Biomass equations and carbon content of aboveground leafless biomass of hybrid poplar in Coastal British Columbia, Forest Ecology and Management, 223:291–302. Salix humboldtiana Salix viminalis Myrcine coriacea B (cm, kg) http://www.globallometree. Myrcine guianensis org/data/equation/15543/ Acacia melanoxylum B (cm, kg) http://www.globallometree. org/data/equation/13521/ Alnus acuminata B (cm, m, kg) http://www.globallometree. org/data/equation/15430/ Liquidambar styraciflua B (cm, m, kg) Thomas M. Williams, Charles A. Gresham, 2006. Biomass accumulation in rapidly growing loblolly pine and sweetgum, Biomass and Bioenergy, 30: 370–377. Annona cherimola Magnolia grandiflora Platanus acerifolia Grevillea robusta B (cm, kg) A. Specht, P.W. West, 2003. Estimation of biomass and sequestered carbon on farm forest plantations in northern New South Wales, Australia, Biomass and Bioenergy, 25: 363–379 Ficus benjamina B (cm, m, kg) http://www.globallometree. org/data/equation/21514/ Ficus carica Ficus lyrata Ficus soatensis (bogotensis) Ficus tequendama Ficus luschnathiana Morus alba Morella parviflora B (cm, kg) http://www.globallometree. org/data/equation/15448/ Morella pubescens Palicourea lineariflora Quercus humboldtii Acacia cultriformis B (cm, kg) http://www.globallometree. org/data/equation/16084/ Acacia baileyana ssp. purpurea Acacia decurrens Acacia spp. Bauhinia forficata Calliandra inequilatera Calliandra pittier Calliandra trinerva Dalea coerulea Erythrina edulis Erythrina rubrinervia Inga spuria Paracerianthes lophantha Psolarea pinnata Ulex spp. Weinmannia tomentosa B (cm, kg) http://www.globallometree. org/data/equation/15563/ Laurus nobilis B (cm, kg) Schmitt-Harsh, M., Evans, T. P., Castellanos, E., & Randolph, J. C. 2012. Carbon stocks in coffee agroforests and mixed dry tropical forests in the western highlands of Guatemala. Agroforestry systems, 86: 141–157. F.J. Escobedo et al. / Urban Forestry & Urban Greening 14 (2015) 1040–1053 1051 Appendix A (Continued) Tree genus-species Biomass (B) or volume (V; units) Sourcea Persea americana Ficus elastica V (cm, kg, g cm-13) http://www.globallometree. org/data/equation/22212/ Vallea stipularis B (cm, kg) http://www.globallometree. org/data/equation/15562/ Psidium guajava spp. V (cm, kg, g cm-13) http://www.globallometree. org/data/equation/23070/ Syzygium jambos Syzygium paniculatum Hevea brasiliensis B (cm, kg) http://www.globallometree.

org/data/equation/16889/ Baccharis macrantha B (cm, kg) http://www.globallometree. Criptoniopsis bogotana org/data/equation/15557/ Clusia insignis B (cm, kg) http://www.globallometree. org/data/equation/15476/ Clusia multiflora Garcinia mangostana Vismia macrophilla Piper bogotense B (cm, kg) http://www.globallometree. org/data/equation/17288/ Araucaria araucana B (cm, kg) http://www.globallometree. org/data/equation/32250/ Araucaria excelsa Chamaecyparis lawsoniana Cupressus sempervirens Thuja spp. Sambucus nigra B (cm, kg) http://www.globallometree. org/data/equation/16572/ Schinus molle Schinus molle Schinus terebinthifolius Acca sellowiana B (cm, kg) http://www.globallometree. org/data/equation/846/ Acca sellowiana Agonis flexuosa Callistemon callistemon spp. Callistemon spp. Calycolpus moritzianus Corymbia maculata Eucalyptus calophylla Eucalyptus cinerea Eucalyptus ficifolia Eucalyptus spp. globulus Leptospermum spp. Metrosidero excelsa Myrcianthes leucoxyla Myrcianthes rophaloides Pinus radiata B (cm, kg) http://www.globallometree. org/data/equation/20407/ Pinus spp. Coffea arabica B (cm, kg) Segura, M., Kanninen, M., Suarez, D. 2006. Allometric models for estimating aboveground biomass of shade trees and coffee bushes grown together. Agroforestry systems 68: 143–150. Cordia cylindrostachya Inga fendleriana Juglans neotropica Archontophoenix alexandrae B (m, kg) http://www.globallometree. org/data/equation/15874/ Archontophoenix cunninghamiana Ceroxylon quindiuense Cordlyne australis Opuntia ficus indica Parajubea coccoides Phoenix canariensis Phoenix roebelenii Phoenix canariensis Phoenix dactylfera Phytelephas schotti Syagrus sancona Washingtonia filifera Yucca filifera Abatia parviflora B (cm, kg) Brown, S. 1997. Estimating biomass and biomass change of tropical forests: a primer. 134. United Nations Food and Agriculture Organization (http://www.fao.org/docrep/ w4095e/w4095e06.htm#3. 3biomass estimates of individual) Abutilon × Hybridum Abutilon insigne Acer spp. Alchornea bogotensis Aloysia triphylla Althaea officinalis Axinaea macrophylla Bellucia axianthera Berberis vulgaris Appendix A (Continued) Tree genus-species Biomass (B) or volume (V; units) Sourcea Billia rosea Bocconia frutescens Bougainvillea spp. Brugmansia × Candida Brunfelsia pauciflora Buddleja davidii Bursera simaruba Calycophyllum multiflorum Carica pubescens Cavendishia cardifolia Cecropia petalta Cedrela montana Cestrum nocturnum Chinchona pubescens Citharexylum subflavescens Citrus limonum Citrus nobilis Citrus sinensis Citrus limonum, nobilis, sinensis Coleonema album Cotoneaster multiflora Crataegus monogyna Crescentia spp. Croton croton spp. Cryptomeria japonica Cyathea caracasana Daphnopsis (deaphnopsis) caracasana Delostoma integrifolia Dodonea viscosa Duranta mutisii Duranta mutisilii Ensete ventricosum Eriobotrya japonica Eriobotrya japonica Escallonia pendula Escallonia floribunda Escallonia laevis Escallonia myrtilloides Escallonia spp. Euphorbia cotinifolia Euphorbia pulcherrima Evonymus japonica Fuchsia arborea Fuchsia magellanica Guarea spp. Guazumo ulmifolia Haematoxylon brasiletto Heliocarpus americanus Hesperomeles goudotiana Hibiscus sinensis Hyeronima colombiana Iochroma fuchsioides Jacaranda caucana Lafoensia acuminata Macleania rupestris Malus pumila Malva arborea Mangífera spp. Meriana nobilis Miconia squamulosa Monochaetum venosum Nageia rospigliossi Oreopanax bogotensis Oreopanax incisus Paullina cupana Photinia serrulata Phyllanthus salviifolius Physalis pubascens Pittosporum tobira Pittosporum undulatum Podocarpus oleifolius Polylepsis australis Prumnoptyis montanus 1052 F.J. Escobedo et al. / Urban Forestry & Urban Greening 14 (2015) 1040–1053 Appendix A (Continued) Tree genus-species Biomass (B) or volume (V; units) Sourcea Prunus cerotina var. capuli Prunus domestica Prunus persica Pyracantha angustifolia Pyrus commuis Rhamnus goudotiana Ricinus communis Rosmarinus officinalis Schefflera actinophylla Schefflera bogotensis Schefflera monticola Schefflera spp. Solanum ovalifolium Solanum betaceum Solanum lycioides

Solanum pseudolulo sparmannia africana Sterculia sterculia apetala Strelitzia reginae Streptosolen jamesonii Symplocos theiformes Tabebuia rosea Talauma carcifigrans Tecoma stans Tecomaria capensis Tibouchina lepidota Tibouchina urvilleana Trichantera gigantea Ulmus spp. Xylosma spiculifera Zanthoxylum zanthoxylum spp. Chlorophytum comosum Pinus montezumae B (cm, m, kg) http://www.globallometree. Pinus patula org/data/equation/914/ Caesalpinia spinosa B (mm, kg) http://www.globallometree. org/data/equation/16247/ Senna multiglandulosa Senna viarum a All http://www.globallometree.org/data/ equations are from Henry et al.(2013).